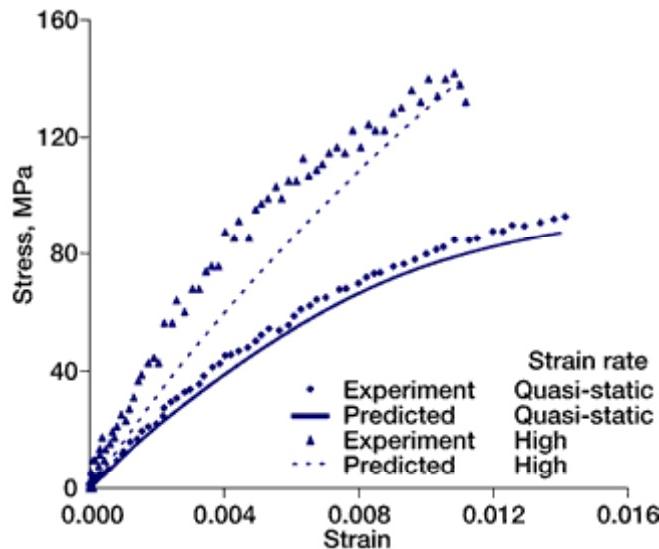


# **Associative Flow Rule Used to Include Hydrostatic Stress Effects in Analysis of Strain-Rate-Dependent Deformation of Polymer Matrix Composites**

Procedures for modeling the high-strain-rate impact of composite materials are needed for designing reliable composite engine cases that are lighter than the metal cases in current use. The types of polymer matrix composites that are likely to be used in such an application have a deformation response that is nonlinear and that varies with strain rate. The nonlinearity and the strain-rate dependence of the composite response are due primarily to the matrix constituent. Therefore, in developing material models to be used in the design of impact-resistant composite engine cases, the deformation of the polymer matrix must be correctly analyzed. However, unlike in metals, the nonlinear response of polymers depends on the hydrostatic stresses, which must be accounted for within an analytical model. By applying micromechanics techniques along with given fiber properties, one can also determine the effects of the hydrostatic stresses in the polymer on the overall composite deformation response. First efforts to account for the hydrostatic stress effects in the composite deformation applied purely empirical methods that relied on composite-level data. In later efforts, to allow polymer properties to be characterized solely on the basis of polymer data, researchers at the NASA Glenn Research Center developed equations to model the polymers that were based on a nonassociative flow rule, and efforts to use these equations to simulate the deformation of representative polymer materials were reasonably successful. However, these equations were found to have difficulty in correctly analyzing the multiaxial stress states found in the polymer matrix constituent of a composite material. To correct these difficulties, and to allow for the accurate simulation of the nonlinear strain-rate-dependent deformation analysis of polymer matrix composites, in the efforts reported here Glenn researchers reformulated the polymer constitutive equations from basic principles using the concept of an associative flow rule. These revised equations were characterized and validated in an experimental program carried out through a university grant with the Ohio State University, wherein tensile and shear deformation data were obtained for a representative polymer for strain rates ranging from quasi-static to high rates of several hundred per second. Tensile deformation data also were obtained over a variety of strain rates and fiber orientation angles for a representative polymer matrix composite composed using the polymer.

To obtain the material data, Glenn's researchers designed and fabricated test specimens of a representative toughened epoxy resin and a representative polymer matrix composite. Quasi-static tests at low strain rates and split Hopkinson bar tests at high strain rates were then conducted at the Ohio State University. To analyze the polymer, Glenn researchers modified state-variable constitutive equations previously used for the viscoplastic analysis of metals to allow for the analysis of the nonlinear, strain-rate-dependent polymer

deformation. Specifically, to account for the effects of hydrostatic stresses, the equations were modified using first principles, with an associative flow rule, a concept developed in basic plasticity theory. This revision modified the calculations of the effective stress and effective inelastic strain from their original definitions and appropriately modified the inelastic flow law. To predict the overall composite deformation, researchers applied a Glenn-developed micromechanics approach in which the predicted response of the composite was computed on the basis of the properties of the individual constituents.

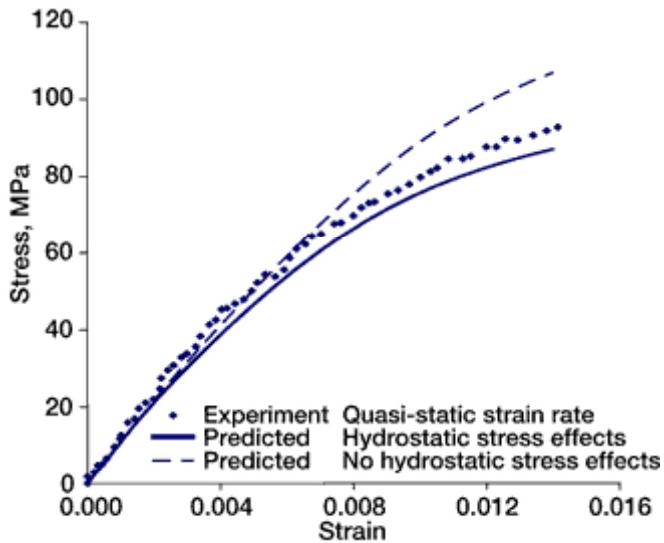


*Experimental and predicted tensile stress-strain curves for a representative [45°] polymer matrix composite at quasi-static and high strain rates.*

Long description. The experimental tensile stress-strain curves display significant nonlinearity for both quasi-static and high strain rates and a significant increase in stress levels as the strain rate is increased.

The computed results qualitatively capture the strain rate dependence and nonlinearity observed in the tensile deformation response, and quantitatively compare well with the experimental values.

The preceding graph shows the experimental and computed tensile stress-strain curves for both quasi-static and high strain rates for a unidirectional [45°] composite. As can be seen in the figure, the nonlinearity and the strain-rate dependence of the composite deformation are correctly computed. The following graph shows the effects of correctly accounting for the hydrostatic stress effects in the polymer on the composite deformation for the quasi-static case. As can be seen in the figure, if the hydrostatic stresses in the polymer are not correctly accounted for, the computed tensile stresses are significantly higher than their experimental values in the nonlinear portion of the stress-strain curve. However, if the hydrostatic stress effects in the polymer matrix are correctly accounted for, the comparison between the experimental and computed curves is reasonably good.



*Effects of hydrostatic stresses on the predicted tensile stress-strain curve for a representative [45°] polymer matrix composite under quasi-static strain-rate loading conditions.*

Long description. If hydrostatic stress effects are not accounted for in the analysis, the predicted stresses, particularly in the nonlinear range, are significantly higher than the experimental values. However, if hydrostatic stress effects are appropriately accounted for, the predicted results compare well with the experimental stress-strain curve.

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